Multipath Tests on 64-m Antennas Using the Viking Orbiter-1 and -2 Spacecraft as Far-Field Illuminators

T. Y. Otoshi
Communications Elements Research Section

D. L. Brunn
R. F. Systems Development Section

Far-field multipath tests were performed on the 64-m antennas at Goldstone, DSS 14, and Madrid, DSS 63, by use of the transponders on the Viking Orbiter-1 and -2 spacecraft. At the time of the tests, Viking Orbiter-1 and -2 spacecraft were in their interplanetary orbits to Mars and were respectively about 21.9 million and 13.9 million km from Earth. The test results showed that the effects of multipath in the far-field of the 64-m antenna were to cause less than a 5-ns peak-to-peak variation on two-way range and 0.1-dB peak-to-peak variations on received signal level. The multipath signal level was calculated to be approximately 40 dB weaker than the primary signal in the far-field main beam direction.

I. Introduction

In a previous article (Ref. 1), it was shown that multipath effects on 64-m antennas could be the cause of the 15-m range residual observed between DSS 43 and DSS 63 during Mariner 10 Mercury Encounter 1 on March 29, 1974. To support this conclusion, however, it was necessary to prove that on the 64-m antenna, the multipath error occurs only in ground station delay calibrations and does not occur in a far-field range measurement to a spacecraft. There was, therefore, considerable interest in performing tests to show that multipath effects in the far-field were negligibly small.

In practice it is difficult to perform a far-field ranging test on the 64-m antenna because, in order to be in the far-field of the 64-m antenna at S-band, the transponder must be located at least 62.8 km (39 mi) away and 5.6 km (3.5 mi) high for a minimum elevation angle of 5 degrees. Due to the non-availability of suitable collimation towers, radiosonde balloons, or satellites for ranging tests, it was necessary to use a spacecraft located in the far-field. A spacecraft that is sufficiently far from Earth will appear like a point source that radiates constant power. Since the ground station tracking antenna can accurately follow any movement of the spacecraft (due to the spacecraft orbit and Earth's rotation), the test conditions are nearly equivalent to those which would be created by a stationary far-field collimation tower in the sky.

The first known far-field test of a large antenna using a spacecraft was reported by Levy et al. (Ref. 2) in 1967. In this test the Surveyor spacecraft on the moon was used as the far-field illuminator. One of the interesting test results obtained was the focus curve shown in Fig. 1. The focus curve shows the relationship of far-field gain changes as a function of subreflector position relative to nominal. It was shown by Potter (Ref. 3) that the ripples observed on the focus curve in Fig. 1 were caused by a multipath component originating from a reflection from the horn aperture. This test result, although restricted to signal level data, presented the first known evidence that a small multipath effect existed in the far-field of the 64-m antenna.

In July 1975, a series of far-field multipath tests was performed on the 64-m antenna at DSS 14 using the ranging transponder on the Helios spacecraft as the far-field illuminator. However, due to the long interplanetary media of about 2 AU and because Helios was only 7 degrees from the Sun as seen from Earth, the differenced range versus integrated doppler (DRVID) and signal level data were excessively noisy. Therefore, no conclusions could be made on far-field multipath effects.

A unique opportunity to perform far-field tests with a spacecraft under ideal conditions came about two months after the launching of the Viking Orbiter (VO) -1 and -2 spacecraft. It is the purpose of this article to present the far-field results obtained with the Viking spacecraft as well as to compare the experimental data with theoretical data.

II. Theoretical Results

As was shown by Potter (Ref. 3), the focus curve for a Cassegrain antenna has a parabolic shape for defocusing losses of less than 1 dB. The approximate expression for the focus curve is

$$G_{dB}(x) \approx (G_0)_{dB} - A_2(x - x_0)^2 \tag{1}$$

where

$G_{dB}(x)$ = antenna gain, dB

$(G_0)_{dB}$ = antenna gain at maximum, dB

A_2 = constant

x = focus position

x_0 = focus position for maximum gain

Figure 2 shows the focus curve of the 64-m tricone system at 2.295 GHz. This curve as based on Eq. (1) has a value for A_2 of 0.02126 dB/cm^2 (0.13716 dB/in.^{2}) for the 64-m tricone configuration (see Potter, Ref. 3). If multipath effects are present in the far-field, they will introduce ripples in the focus curve similar to that shown in Fig. 1.

Although there is a similar focus curve for the uplink frequency of 2.113 GHz, the spacecraft radio system removes the uplink signal level variations and transmits back a constant coherent downlink signal back to Earth. Therefore, in a far-field multipath test, one only needs to consider defocusing losses on the downlink signal at approximately 2.295 GHz.

To the authors' knowledge, no published information is available concerning the far-field group delay and phase delay changes resulting from the defocusing of the subreflector on a Cassegrain antenna. A defocused subreflector computer program written by Sorensen (Ref. 4) was modified by Rusch to yield far-field data for a defocused Cassegrain antenna. The phase versus frequency and phase versus subreflector position data were used to compute far-field group and phase delay changes, respectively. Figure 3 shows the group delay change[1] due to defocusing of a symmetrical Cassegrain antenna in the absence of multipath. The primary feed was assumed to have an E- and H-plane power pattern of (43.63) (20 $\log_{10}$ $\cos \gamma$), which is nearly equivalent to the main lobe power pattern for the Potter horn described in Refs. 5 and 6. The angle γ is the angle from boresight of the primary feed. Although the present 64-m antenna has a corrugated feedhorn and a tricone configuration, it is not expected that the delay change curve for the present configuration would differ significantly from that shown in Fig. 3. For comparison purposes, the dashed curve shows the total (uplink plus downlink) delay change relationship for a single ray traveling only along the axis of the subreflector. It can be seen that the total change in the far-field due to contributions from the entire aperture is slightly less than the delay change for the single on-axis ray.

From the Sorensen/Rusch Program, it was found that the phase delay change was equal to the group delay

[1]The Sorensen/Rusch Program results showed that the phase delay change was the same as group delay change as a function of subreflector position. Therefore, Fig. 3 applies to either phase or group delay changes.

change. Since, by definition, DRVID is group delay change minus phase delay change (Ref. 7), the far-field DRVID data should show no change as a function of subreflector position. However, if there is a multipath effect in the far-field, the group delay changes will be much larger than phase delay changes and a cyclical variation on DRVID data will be observed due to subreflector movement.

III. Experimental Results

A. VO-2 Tests at DSS 14

On October 23, 1975, a far-field test was performed with the VO-2 spacecraft at DSS 14. At the time of the test the VO-2 spacecraft was approximately 13.9 million km from Earth. A strong received signal level of –136 dBm and a good ranging power-to-noise ratio of 33 dB were prevalent at DSS 14 during the far-field ranging tests. Other favorable conditions for this test were the short round-trip light time (RTLT) of 93 seconds and the absence of any solar and ionospheric effects introduced into the DRVID data. A short RTLT was desirable for the far-field multipath test because a short RTLT is equivalent to a short interplanetary medium. A shorter interplanetary medium generally has less electron content than a longer one, and, therefore, the DRVID data will be less likely to change due to electron density changes. No ionospheric or solar effects were introduced because the tests at DSS 14 were done during night-time hours.

The far-field multipath test consisted of ranging to the spacecraft and recording DRVID and received signal level data as a function of subreflector positions. For this test, the subreflector was moved in 1.27-cm (0.5-in.) increments over a total distance of 15.24 cm (6 in.). The test began and ended with the subreflector at the nominal setting so that one could observe and remove the long-term drift in the test data.

The experimental test results may be seen in Figs. 4–7. Figure 4 shows the results of taking 4 hours of DRVID data while moving the subreflector and 2 hours of data while keeping the subreflector stationary for comparison purposes. The drift in the DRVID data during the 4-hour multipath test was about 10 ns. After removing this drift by fitting a second-order curve to the experimental data, the residual differences at each subreflector position were then averaged. A least squares fit of the multipath equation was then made to the averaged DRVID points by use of the Multipath Computer Program described in Ref. 1. The resulting plot shown in Fig. 5 shows relatively good correlation between calculated and experimental values. The peak-to-peak change in range delay was about 3 ns. The Multipath Program calculated the multipath signal to be –45 dB relative to the primary signal in the far-field. This relative multipath signal strength will produce a ripple of 0.1 dB in the downlink received signal level focus curve.

Figure 6 shows the downlink received signal level data obtained during the far-field multipath tests. A comparison of experimental and theoretical results may be seen in Fig. 7. The experimental points were obtained from averaging the received signal level values at each subreflector setting and normalizing them to the received signal level value at the 0 in. position.[2] A least squares parabolic curve was then fitted to the experimental data points. For comparison purposes, the peak of the tricone theoretical curve (Fig. 2) was aligned with the peak of the experimental curve. It can be seen that excellent agreement was obtained between theory and experiment. The deviations of the data about the experimental curve are consistent with the deviations caused by a multipath signal being –45 dB with respect to the principal wave.

For purposes of comparison, the results of pre-cals done with the zero delay device at DSS 14 are shown in Fig. 8. It can be seen that the peak-to-peak variations are 40 ns and 3 dB for range delay and received signal level, respectively. One explanation as to why a small multipath effect occurs in the far-field measurements but a large effect occurs in zero delay calibrations is the following: The primary waves impinging on the paraboloidal dish surface add up in phase in the far-field. Although the multipath wave signal strengths at a localized area can be as strong as –15 dB relative to that of the primary wave, the multipath waves are not the same in phase or amplitude over the entire dish surface. Therefore, when the multipath components combine in the far-field, they do not necessarily add in phase. Since cancellations can occur, it is not unreasonable that the net far-field multipath signal level can be –45 dB relative to the primary wave in the main beam.

B. VO-1 Tests at DSS 63

On October 26, 1975, a far-field multipath test was also performed at DSS 63. This test was similar to the DSS 14 test but differed in that the VO-1 spacecraft was used instead of VO-2. The RTLT was 146 seconds, which indicates that the VO-1 spacecraft was approximately 21.9

[2] The subreflector position on the equipment is indicated in inches rather than in centimeters. In order for data to be meaningful and be useful to the user and also to avoid double conversions, the units should be kept in inches as reported.

million km from Earth. VO-1 was farther from Earth than VO-2 was; therefore, the received signal level was weaker. The ranging power-to-noise ratio was 22 dB as compared to 33 dB obtained with VO-2. In order to eliminate ionospheric and solar effects, the test at DSS 63 also was done during night-time hours.

Although far-field data had already been successfully obtained at DSS 14 with the VO-2 spacecraft, the test was performed at DSS 63 because the DSS 63 64-m antenna was known to have the largest multipath effect (Ref. 1) and also had a cone missing. These differences in ground station configurations could cause far-field multipath effects to differ.

Figure 9 shows the DRVID data during the 3-hour period that the subreflector was being moved. It may be seen that there was virtually no drift in the DRVID data during the test. Because this was an abbreviated test, DRVID stability data with the subreflector stationary were not obtained during the same VO-1 pass. However, examination of DRVID stability data at DSS 63 for a VO-2 pass three days later showed that the DRVID drift between 0000 GMT and 0700 GMT was only 10 ns. Therefore, it can be reasonably assumed that the drift during the DSS 63 VO-1 test was also small.

Figure 10 shows a comparison of the averaged experimental DRVID data at each subreflector setting and a best fit theoretical curve which is based on the multipath equations (Ref. 1). Although there is only partial agreement between theory and experiment, the peak-to-peak variation of range delay is only about 5 ns. The multipath signal was calculated to be 39 dB weaker than the primary signal in the far-field.

Figure 11 shows the experimental received signal levels during the multipath test. In Fig. 12, which shows the normalized plot, each data point is the result of averaging data at each subreflector position. A comparison of a least squares parabolic curve (fitted to the experimental data points) and the theoretical curve for the tricone configuration may be seen in Fig. 12. It can be seen that the agreement between the experimental parabolic curve and the theoretical curve is reasonably good. Although the agreement between theory and experiment is not as good as that obtained in the DSS 14 VO-2 tests, it should be pointed out that at DSS 63, the 64-m antenna has a cone missing. In addition, the received signal level with VO-1 was 10 dB lower than that on the VO-2 tests, and therefore, the data were noisier.

IV. Conclusions

Good experimental results were obtained from the far-field multipath tests on the 64-m antennas at DSS 14 and DSS 63 and the two Viking spacecraft. The far-field multipath effects were found to be small. The variations due to subreflector movement were typically less than 5 ns peak-to-peak on total range delay and less than 0.1-dB cyclic variation on received signal level.

The excellent results obtained from Viking spacecraft can be attributed to a good ranging power-to-noise ratio (>20 dB), a short RTLT (<3 min), and the absence of solar or ionospheric effects.

Acknowledgments

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References

1. Otoshi, T. Y., "S-Band Zero-Delay Device Multipath Tests on the 64-m Antenna at DSS 43, DSS 63, and DSS 14," in *The Deep Space Network Progress Report 42-29*, pp. 20–30, Jet Propulsion Laboratory, Pasadena, CA, Oct. 15, 1975.

2. Levy, G. S., et al., "Lunar Range Radiation Patterns of a 210-Foot Antenna at S-Band," *IEEE Transactions on Antennas and Propagation*, Vol. AP-15, No. 2, pp. 311–313, March 1967.

3. Potter, P. D., "Network Engineering and Implementation: S- and X-Band Feed Systems," in *The Deep Space Network Progress Report*, Technical Report 32-1526, Vol. X, pp. 135–140, Jet Propulsion Laboratory, Pasadena, CA, Aug. 15, 1972.

4. Sorensen, O., "Application of the Geometrical Theory of Diffraction to Cassegrain Subreflector with Laterally Defocused Feeds," Masters' Thesis, Lab. Electromagnetic Theory, Tech. University Denmark, Lyngby, Fall 1973.

5. Potter, P. D., "A New Horn Antenna with Suppressed Sidelobes and Equal Beamwidths," *Microwave J.*, Vol. 6, No. 6, pp. 71–78, June 1963.

6. Otoshi, T. Y., and Stelzried, C. T., "Improved RF Calibration Techniques: Cosmic Background Noise Temperature Measurements at 13 cm," in *The Deep Space Network*, Space Programs Summary 37-57, Vol. II, pp. 90–100 (for horn pattern data at S-band, see Fig. 59, pp. 96–97), Jet Propulsion Laboratory, Pasadena, CA, May 31, 1969.

7. MacDoran, P. F., "A First-Principles Derivation of the Differenced Range Versus Integrated Doppler (DRVID) Charged-Particle Calibrations Method," in *The Deep Space Network*, Space Programs Summary 37-62, Vol. II, pp. 28–34, Jet Propulsion Laboratory, Pasadena, CA, Mar. 31, 1970.

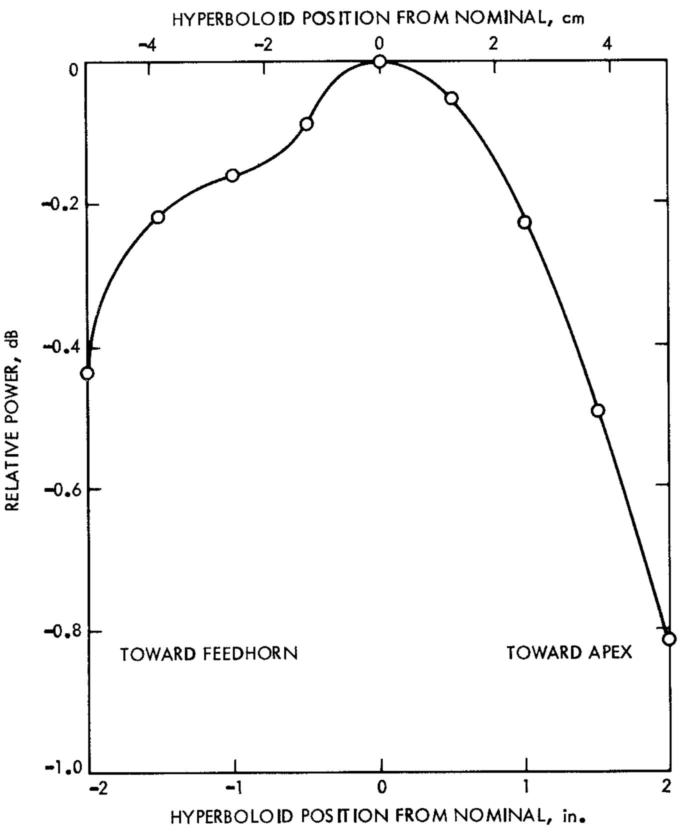

Fig. 1. 64-m antenna Surveyor focus curve (from Ref. 2)

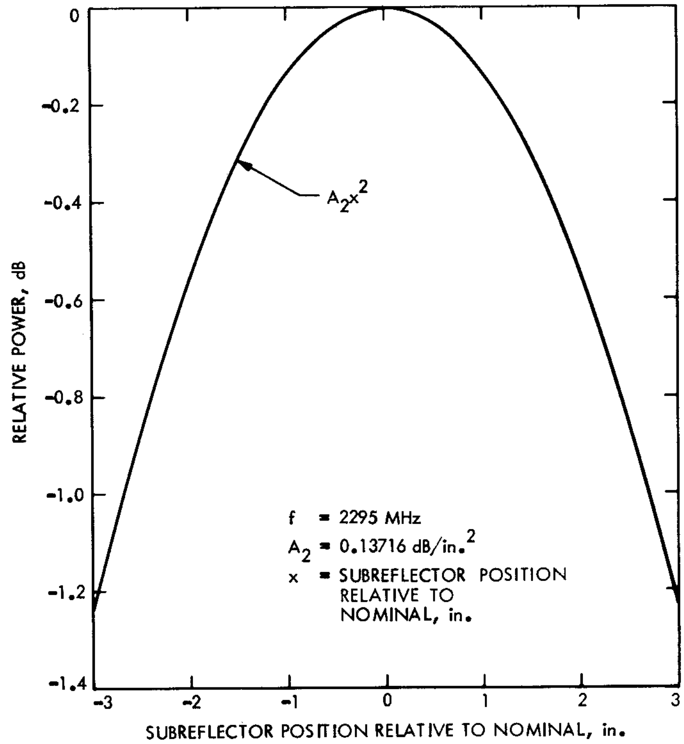

Fig. 2. Far-field focus curve from 64-m Cassegrain antenna tricone configuration in the absence of multipath

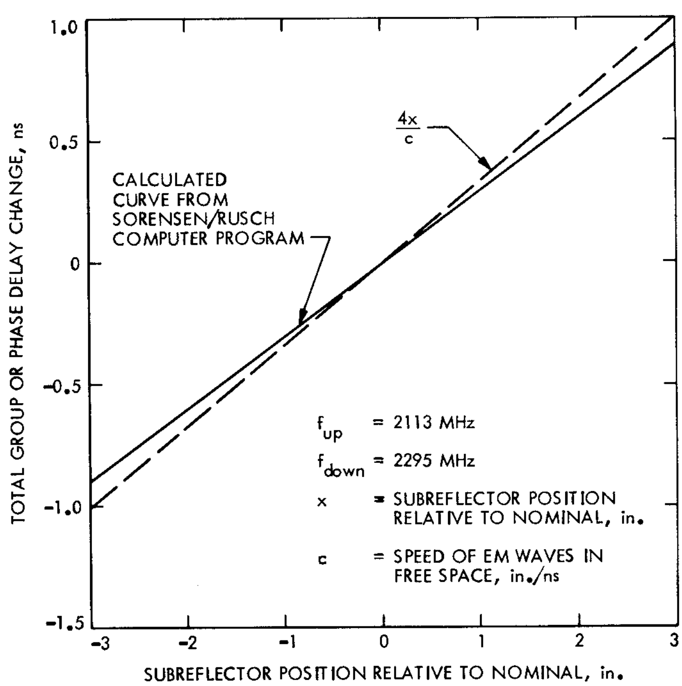

Fig. 3. Total uplink plus downlink phase or group delay change in the far-field of a defocused 64-m Cassegrain antenna in the absence of multipath

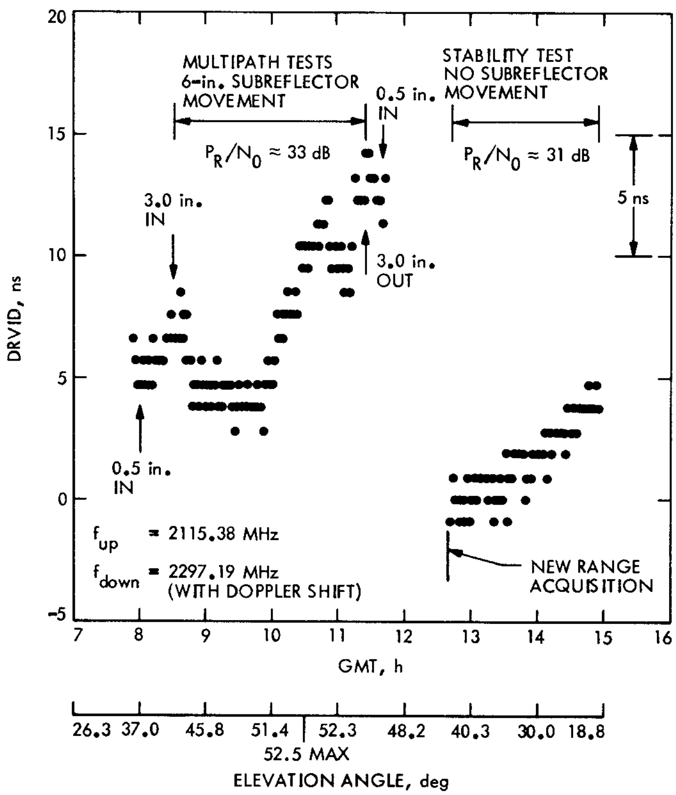

Fig. 4. Original DRVID data from DSS 14 VO-2 spacecraft multipath test on 1975 GMT Day 296. Polarization is RCP.

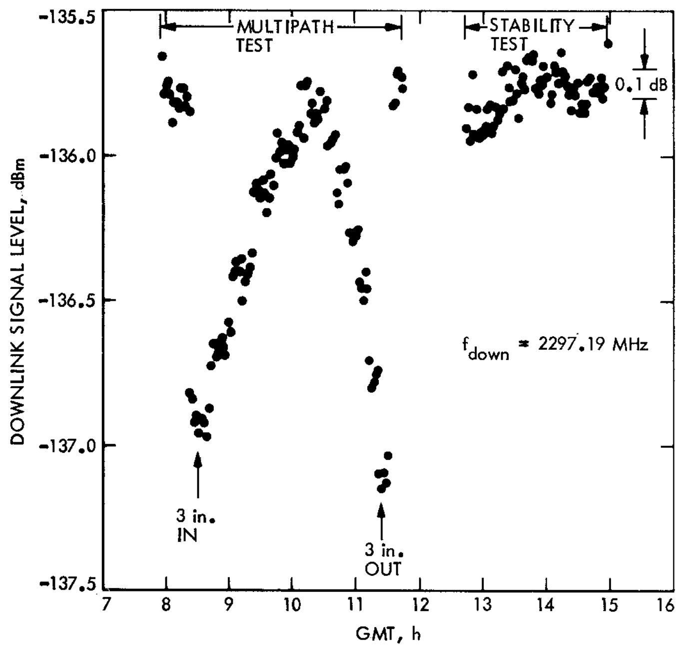

Fig. 6. Received signal level during DSS 14 VO-2 multipath test on 1975 GMT Day 296. Polarization is RCP.

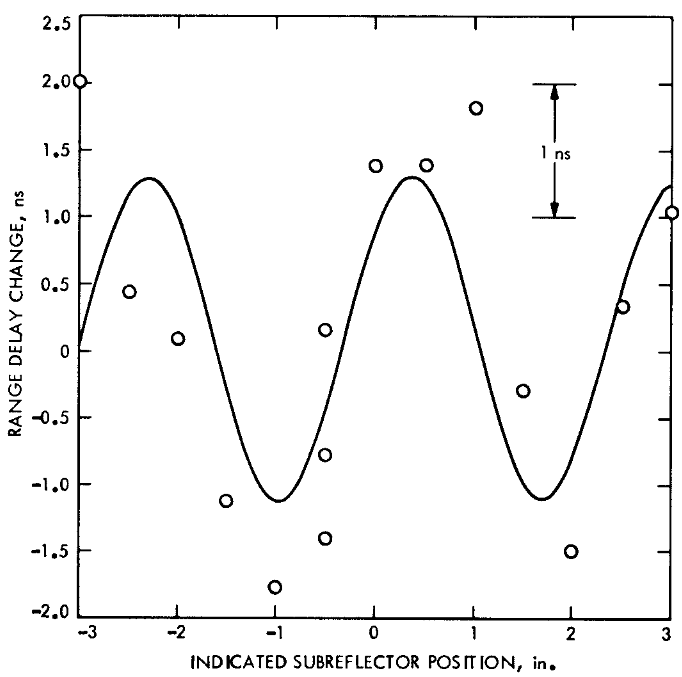

Fig. 5. Reduced DRVID data from DSS 14 VO-2 spacecraft multipath test on 1975 GMT Day 296

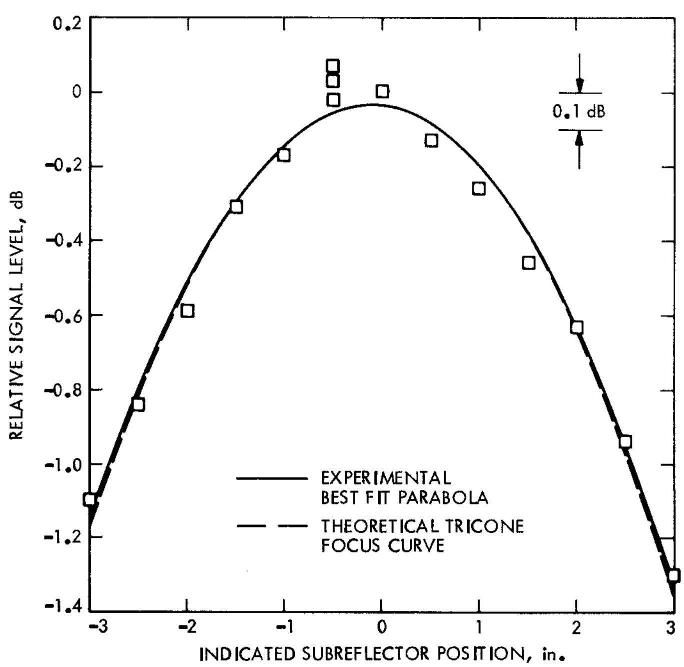

Fig. 7. Theoretical and experimental results for relative received signal level on DSS 14 VO-2 multipath test on 1975 GMT Day 296

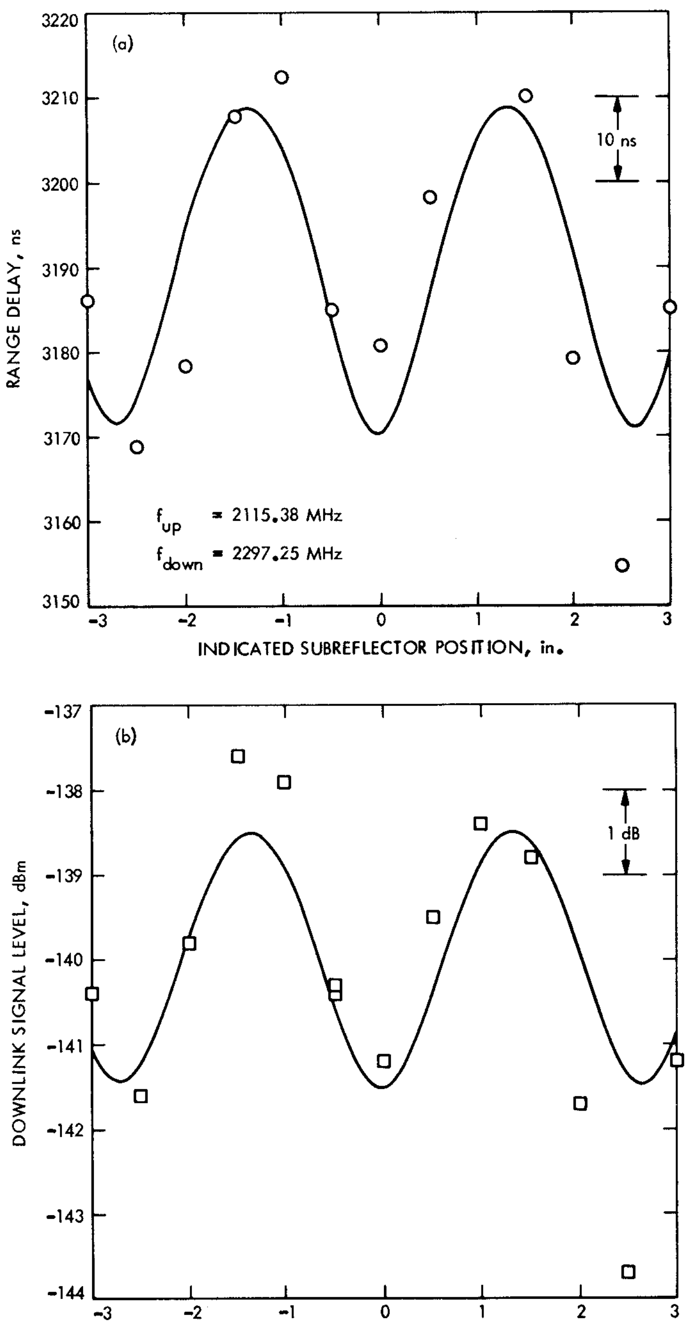

Fig. 8. Theoretical and experimental results for multipath tests on DSS 14 VO-2 Pass 44 pre-cal on 1975 GMT Day 296. Polarization is RCP.

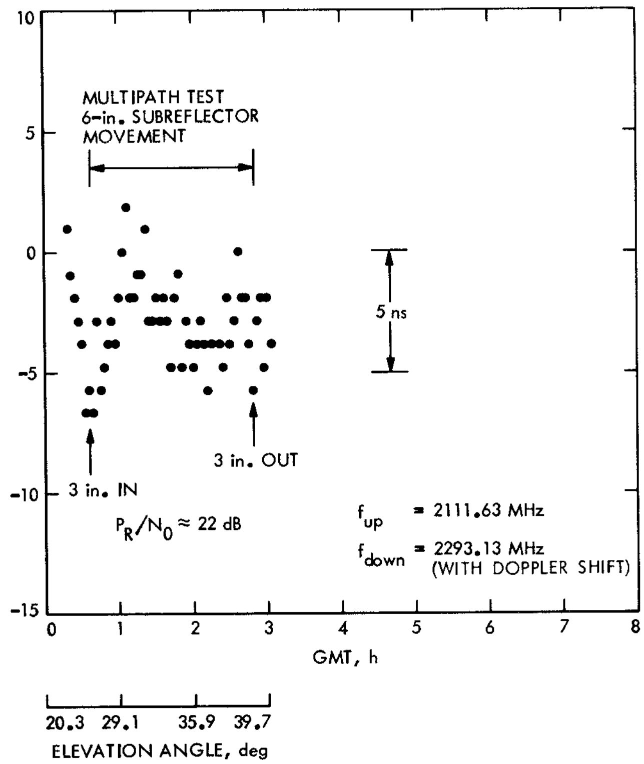

Fig. 9. Original DRVID data from DSS 63 VO-1 spacecraft multipath test on 1975 GMT Day 299. Polarization is RCP.

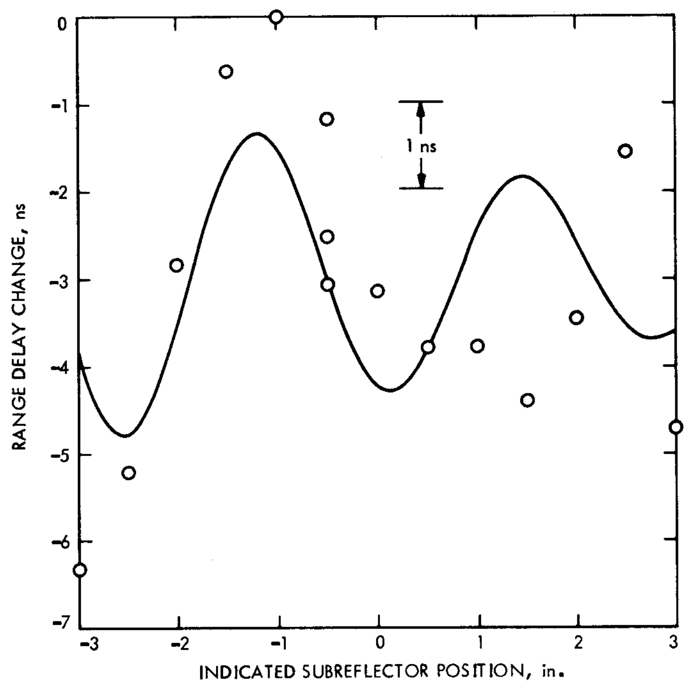

Fig. 10. Reduced DRVID data from DSS 63 VO-1 spacecraft multipath test on 1975 GMT Day 299

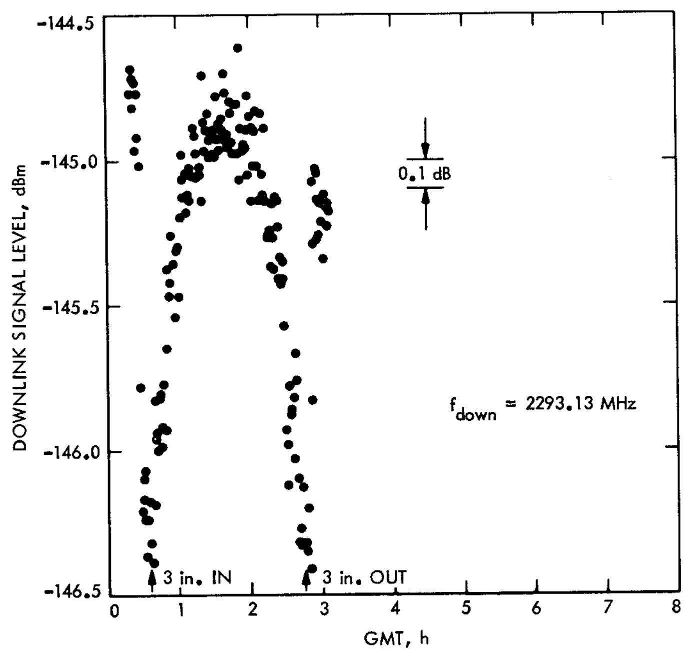

Fig. 11. Received signal level during DSS 63 VO-1 multipath test on 1975 GMT Day 299. Polarization is RCP.

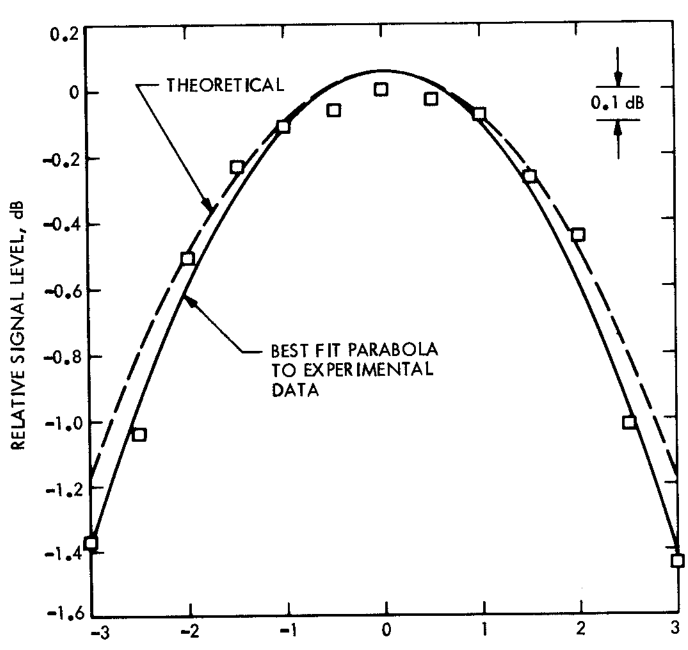

Fig. 12. Theoretical and experimental results for relative received signal level on DSS 63 VO-1 multipath test on 1975 GMT Day 299